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Integrated assessment of regional approaches for biodiversity offsetting in urban-rural areas – A future based case study from Germany using arable land as an example

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ABSTRACT

Human interventions, i.e. settlement and construction activities, in the agricultural landscape including farmland but also natural and semi-natural habitats are a major driver of biodiversity loss. Consequently, their impacts on nature and landscape have to be compensated by no net loss policies in many countries around the world. However, their practical implementation often poses challenges with regard to the optimal spatial coordination and assessment of measures, especially in the case of eco-accounts or other habitat banking approaches.

Against this backdrop, different approaches to offset biodiversity loss at regional level are analysed with due consideration of indicators of economy, ecology, landscape aesthetics and food production. We used an interdisciplinary modelling approach based on estimates for offsetting demand until 2030. In the integrated land use model, we associated a biophysical crop growth model with an economic optimisation model. The Stuttgart Region – an area with stiff competition amongst anthropogenic land use patterns in Germany – served as the study area. Our main focus was on arable land that has a high potential for nature conservation enhancement. In this context, farmers are deemed to be a major stakeholder group.

We observed differing economic and ecological outcomes for the offsetting scenarios we considered. In urban areas with high population density and low biodiversity (e.g. Stuttgart city), compensation close to the site of intervention (on-site) may be more expensive than off-site compensation. However, further added value can be generated by on-site compensation in terms of visual landscape quality enhancement and habitat connectivity, provided that the measures lend themselves to establishing connectivity. Consequently, spatially unrestricted markets for eco credits may exacerbate ecological polarisation between urban and rural areas. Therefore, we concluded that offset site selection should not be driven solely by economics, as this may not optimise overall welfare from a societal perspective, resulting in the need for legal constraints.

Our results show the trade-offs between the political goals of spatial planning approaches and compensation strategies. They can, therefore, thus provide valuable information that enables political decision-makers to more clearly weigh up the effects of policy measures in this area.

1. Introduction

1.1. Basic principles of impact mitigation regulation in Germany and criteria for offset implementation

Habitat loss due to anthropogenic influences, such as urbanisation and infrastructure development, is one of the main causes of biodiversity decline (Fletcher Jr et al., 2018; IPBES, 2019; Laurance et al., 2015; McKinney, 2006). In terms of the Sustainable Development Goals (SDGs), economic prosperity (SDG 9) and nature conservation (SDGs 14 and 15) often lead to conflicting objectives that are difficult to reconcile (zu Ermgassen et al., 2019).

In this context, biodiversity offsets are increasingly being implemented as part of No Net Loss (NNL) policies in many countries worldwide in the aftermath of the early offsetting attempts in the US and in Germany in the 1970s that sought to resolve this trade-off (Bull and

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Strange, 2018; Coralie et al., 2015; Maron et al., 2016). Offsetting is the last step in the mitigation hierarchy in which avoidance and minimisation are to be prioritised (Arlidge et al., 2018; Darbi, 2020). Consequently, it is crucial to produce detailed and precise predictions of loss of biodiversity and habitats caused by the respective intervention in the natural balance (Bull and Strange, 2018). In Germany, offsetting is based on the Impact Mitigation Regulation (IMR) (Albrecht et al., 2014) with Article 13 of the German Nature Conservation Act (*BNatSchG*) as the legal foundation. This Article specifies that unavoidable significant adverse effects on nature and landscape, for instance due to any kind of development, are to be offset by appropriate compensation or substitution measures. In this context, the term compensation refers to in-kind and on-site measures, whereas substitution means out-of-kind and off-site measures. For the latter, a close spatial and functional relationship to the intervention is not required (Tucker, 2016; Wende et al., 2018). However, since the amendment of the IMR in the *BNatSchG* 2010, equal priority has been given to compensation and substitution by law (Michler and Möller, 2011).

In general, the implementation of biodiversity offsets is dependent on suitable sites. Various approaches exist, whereby many offset programmes set quite loose requirements regarding the spatial relationship between the intervention and the offset sites (Gordon et al., 2011). This is also evident in the above-mentioned example of substitution measures in the German IMR. Efficient planning is the key to achieving a high degree of ecological effectiveness of biodiversity offsets or an impact on the aesthetic quality of landscapes. In general, different implementation strategies can be derived, such as systematic conservation planning on the landscape level or a project-by-project approach (Kiesecker et al., 2010). A regional strategy for the implementation of biodiversity offsets must, therefore, include relevant stakeholders in the development process (Kiesecker et al., 2010). According to the German Environment Agency (Umweltbundesamt, 2020) agriculture accounts for more than 50% of the total area in Germany and farmers are major stakeholders in this process (Koh et al., 2019; Primmer et al., 2019; Taherzadeh and Howley, 2018; Vaissière et al., 2018). Furthermore, agricultural land is quite often used for offsetting purposes and is thus frequently no longer available for production (Tietz et al., 2012). Therefore, in addition to land use for settlement and construction areas, offset measures can lead to additional consumption of agricultural land often resulting in land use conflicts (Le Coent et al., 2017).

By using eco-accounts as a form of habitat banking, agriculture can be actively involved in the compensation process. Farmers can implement suitable measures on their land, generate eco credits as a unit of the ecological value of an area, and sell them freely on the market (Czybulka et al., 2012; Druckenbrod and Beckmann, 2018). In principle, these offset measures must then be maintained for as long as the intervention lasts, i.e. usually on a permanent basis (MLR, 2011). However, a limitation of the maintenance period to 25 years, for example, is possible, if it can be assumed that the intended habitat created is then self-sustaining (Fellenberg, 2016; Lütkes et al., 2018). This is not usually the case with pure maintenance and management measures. They are, in fact, to be implemented and maintained for an unlimited period of time (Giesberts and Reinhardt, 2020). In the context of possible cooperation between nature conservation and agriculture, eco-accounts may also offer advantages from the landscape planning perspective. Generally speaking, the establishment eco-accounts should facilitate the improved implementation of measures from an ecological perspective and the sensible planning and coordination of measures, for example, the grouping of offset measures in larger projects (Mazza and Schiller, 2014; Wende et al., 2018). Consequently, spatial planning on the landscape level for the implementation of biodiversity offsets is especially important for the success of such mitigation banking approaches (ten Kate and Crowe, 2014).

1.2. *The objectives of our study and underlying research questions*

As mentioned above, offsetting is associated with long-term decision-making. This requires careful planning to generate ecological values, taking into account effects such as climate change and regional food supply. In the strategic offset planning process, the respective effects of different strategies can be demonstrated to decision-makers by way of land use modelling (Gordon et al., 2011). In this context, the assessment of ecosystem services, such as human well-being is still a major challenge, but process models, for example, are used to link them to the biophysical domain. Many studies focus mainly on the associated ecological aspects, but rarely consider the social or economic aspects (Gelcich et al., 2017). Therefore, in this study we considered different compensation strategies at regional level that included agriculture as an important stakeholder in the overall process of spatial offset planning from an economic perspective. For this, the economic assessment of the offset measures on agricultural land at local level also requires high resolution information about crop yields that influence the opportunity costs of compensation, and are important for the assessment of regional food supply. Noticeable effects of climate change on crop yields are expected in Baden-Württemberg and, on a comparatively large scale, in parts of the Stuttgart Region, which should also be taken into account (UMBW, 2015).

We assumed that strategic planning of measures with the participation of relevant stakeholders plays an essential role, especially in densely populated urban areas with a high level of construction activity and a correspondingly high need for compensation. The Stuttgart Region (https://www.region-stuttgart.de/) in the Federal State of Baden-Württemberg, Germany – a steadily growing conurbation – is one such area and it served as our study area. The future need for offsetting until 2030 was estimated by the regional planning association at the level of the municipalities (Verband Region Stuttgart) and made available for our study (Jenssen, 2020a). From a nature conservation point of view, arable land in particular is classified as being of rather low value, with a correspondingly high potential for improvement (BVerwG, 2004). Against this backdrop, offset measures are also considered relevant in the context of future arable farming systems in Germany with regard to their potential for improving biodiversity in the agricultural landscape (Bahrs et al., 2020). We, therefore, focused on implementing biodiversity offsets on arable land in our analysis. According to Sponagel et al. (2021), farmers are generally willing to implement biodiversity offsets on a voluntary basis. However, this also depends on the monetary compensation. To anticipate farmers' acceptance of offset measures, the willingness to accept (WTA) derived from discrete choice experiments (DCEs), for example, can be used to assess the costs more realistically, i.e. including a certain risk surcharge on the price (Koh et al., 2019; Petig et al., 2019).

The implementation of offset measures generally requires legal security, for instance, a land register entry (Lütkes et al., 2018). This basically rules out any other use of the field plot in future. In this context, Lehn and Bahrs (2018) as well as Mährlein and Jaborg (2015) already identified a potential negative impact on the market value of agricultural land through its mere designation as a protected area such as Natura 2000. Therefore, the securing of offset measures in the land register can also impact the market value of the land, and influence farmers' acceptance of biodiversity offsets (Busse et al., 2019). The relatively large differences in purchase prices for agricultural land in the region alone can, therefore, effect offsetting costs (Stat. Landesamt BW, 2020b). Implementing biodiversity offset measures off-site at the landscape level might lead to lower costs (Moilanen and Kotiaho, 2018; Tallis et al., 2015). From a societal perspective, the effect on the local population at the site of intervention should also be considered (Jones et al., 2019; Moreno-Mateos et al., 2015). Intervening parties who have to bear the offsetting costs could therefore have an incentive to implement the measures where they are most cost-effective, provided there are no further spatial restrictions (Calvet et al., 2015). However, if offsetting shifts from areas with high construction activity to areas with low development pressure and also low economic opportunity costs for implementing offset measures, the additional added value from an ecological perspective may be limited (zu Ermgassen et al., 2020).

Habitat banking also requires a metric unit for assessing offset measures. In Baden-Württemberg this is done in accordance with the Eco Account Regulation (*ÖKVO*). The valuation in eco credits is based on the difference between the initial condition and the target condition of a habitat type. However, there is no standardised assessment method to quantify aesthetic value in eco credits. Instead, this is mostly done through expert assessment on a case-by-case basis (Darbi and Tausch, 2010; Mazza and Schiller, 2014). Consequently, landscape aesthetics are often neglected in planning practice (Fischer and Roth, 2020). However, studies have also shown that if the landscape is taken into account, societal acceptance and implementation can be promoted (Wende et al., 2009). Hence, the question arises whether this aspect is sufficiently taken into account in a purely economic optimisation (Calvet et al., 2015).

On this foundation, we addressed to following research questions.

R1. Can agriculture in metropolitan regions still provide land for offset measures despite the high pressure on land?

R2. Do the spatial location and coordination of compensation measures in relation to the site of intervention have a major impact on the compensation costs?

R3. Could additional benefits for nature conservation and landscape aesthetics be achieved beyond the legal obligations, depending on the spatial coordination of the measures?

R4. Could spatially unrestricted market mechanisms for offset measures lead to polarisation in terms of ecological and cultural landscape quality between urban and rural areas?

R5. How does the spatial planning of offset measures impact regional food supply from the perspective of the effects of climate change?

The costs and other impacts associated with the implementation of biodiversity offsets on arable land in the Stuttgart Region were analysed using the geodata-based linear programming model PALUD (Parcel based agronomic land use decision model) in different scenarios for compensation. Based on data from the national IACS (Integrated Administration and Control System) database provided by the Ministry of Rural Affairs and Consumer Protection Baden-Württemberg, field-specific crop rotations and gross margins were mapped. The yield capacities of the agricultural fields affected by climate change until 2050 were simulated using the bio-physical crop growth model Expert-N (Biernath et al., 2011; Priesack, 2006; Wöhling et al., 2013). The predicted yields were fed into the PALUD economic optimisation model. Finally, we also examined the relationship between offsetting and landscape aesthetics, an important conservation subject in the IMR, and obtained related biodiversity indicators.

2. Characterisation of the Stuttgart Region with regard to offsetting

The Stuttgart Region consists of 179 municipalities within the six administrative districts Stuttgart, Ludwigsburg, Rems-Murr-Kreis, Göppingen, Esslingen and Böblingen (Table 1). Measured by gross value added, the Stuttgart Region is one of the strongest economic regions in Germany (Dispan et al., 2019). While the Stuttgart Region covers about 10% of Baden-Württemberg's land area, it accounted for 16% of Baden-Württemberg's land consumption by settlement and infrastructure in the period from 2000 to 2016. This demonstrates the importance of targeted biodiversity offsetting in this region (LUBW, 2018). Strong regional disparities in terms of the natural environment, economy and demographic development also characterise the region. The district of Böblingen stands out as the area with the highest productivity and economic growth (IREUS, 2020). These spatial disparities are also reflected in the different future demands for offsetting according to Jenssen (2020a). Housing and industrial will account for two-thirds of the total offset demand in the region until 2030 and were recorded at the municipal level. In addition, the demand for transport infrastructure, wind energy and raw material extraction was initially recorded at the district level and distributed to the municipalities in equal shares. All in all, this resulted in the total offset demand at the municipality level (Table 1).

Table 1
Overview of the future demand for biodiversity offsetting measured in eco credits for the Stuttgart Region by district until 2030 (Jenssen, 2020a).

Urban/rural district	Total demand for eco credits in millions	Number of municipalities	Average demand for eco credits per ha arable land
Böblingen	170	26	11,495
Esslingen	150	44	15,489
Göppingen	120	38	9990
Ludwigsburg	190	39	8102
Rems-Murr-Kreis	140	31	12,541
Stuttgart	5	1	3759
Stuttgart Region	775	179	10,700

Spatial disparities also characterise agricultural land use in the Stuttgart Region. There are 128,024 ha of utilised agricultural area (UAA), of which 72,430 ha or 57% are used for arable farming. This accounts for 77,698 field plots. The highest share and volume of arable land (ARA) is found in the district of Ludwigsburg with about 76% and 23,440 ha respectively, whereas the districts of Göppingen und Rems-Murr-Kreis are characterised by a high proportion of permanent grassland (Fig. 1).

In the city district of Stuttgart and the district of Esslingen, crops such as vegetables and fruit are grown on a much higher share of arable land than in the rest of the region (Stuttgart: 10%, Esslingen 9%, rest between 0.2% and 0.9%). The share of cereals within the crop rotation is generally high and ranges between 55.3% and 63.9% in the region (Fig. 2).

3. Material and methods

3.1. Land use modelling

3.1.1. Description of the integrated land use model

Fig. 3 gives an overview of the modelling framework with the Expert-N and PALUD models and the respective input and output data. The individual model components are explained below.

3.1.2. Economic evaluation of arable land use with crop growth modelling in Expert-N

The agro-ecological process model library Expert-N 5.14 (Heinlein et al., 2017; Klein et al., 2017; Priesack, 2006) was used to quantify attainable crop yields for seven selected crop types by numerical modelling of soil-plant processes, thereby accounting for future rises in atmospheric CO_2 levels and changes in meteorological conditions. Plant growth, photosynthesis, and evapotranspiration were modelled with GECROS (Yin and van Laar, 2005). In Expert-N, GECROS was coupled with the Richards equation for simulating variably saturated water flow in soil using the HYDRUS model (Simunek et al., 1998), with the heat transport, carbon and nitrogen mineralisation components of the DAISY model (Abrahamsen and Hansen, 2000), and with LEACHN (Hutson and Wagenet, 1992) for the simulation of the remaining nitrogen processes.

The information to parameterise and setting up the soil modules was taken from the digital soil map 1:50,000 (BK 50) (LGRB, 2015). This soil map has the highest resolution in Baden-Württemberg. Two different

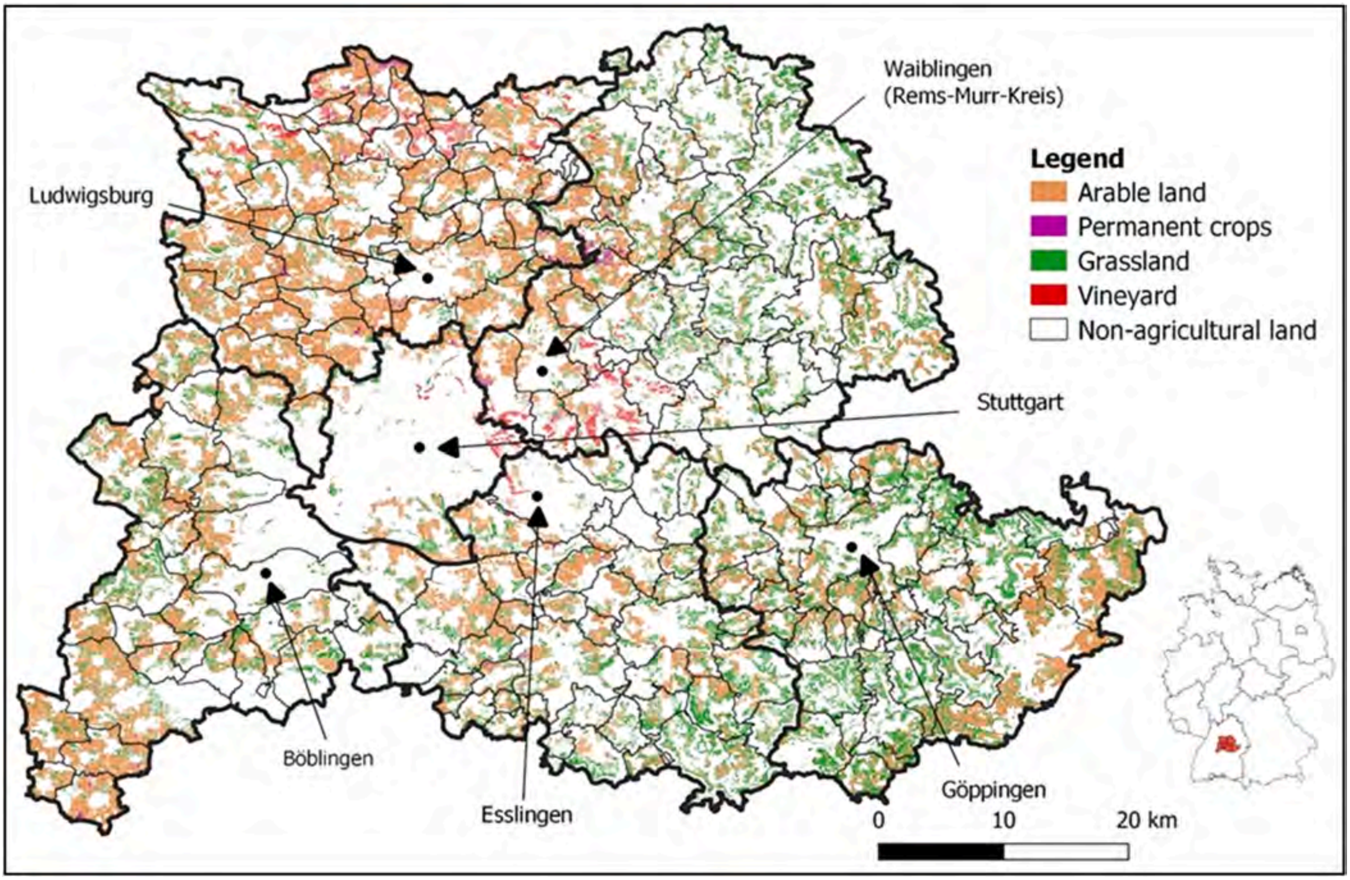

Fig. 1. Overview of land use in the Stuttgart Region, and the districts with the principal district towns, and municipalities as administrative units (based on data from the IACS database 2019 provided by the Ministry of Rural Affairs and Consumer Protection Baden-Württemberg, ALKIS (2018) and BKG (2018)).

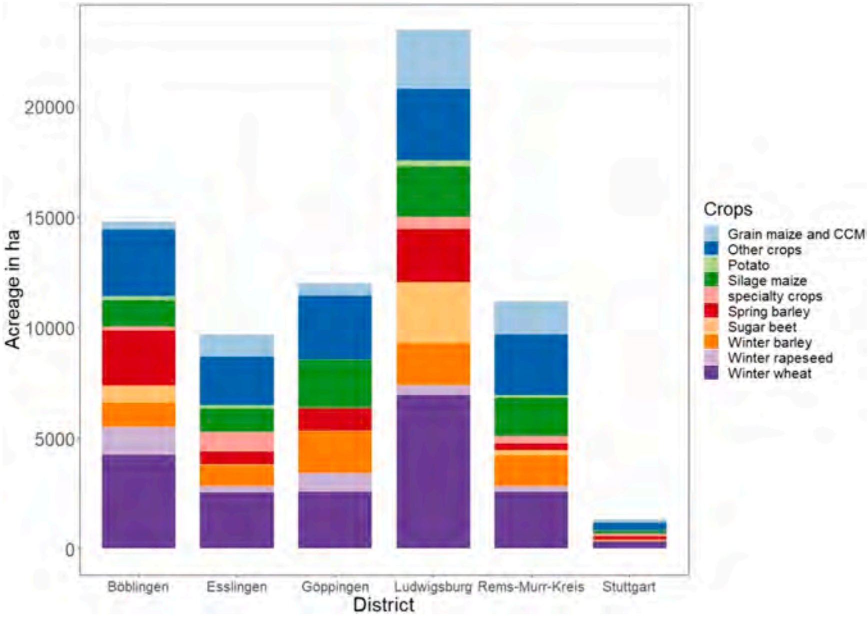

Fig. 2. Overview of arable land use per district in the Stuttgart Region in 2019 (based on the data of the IACS database 2019).

daily data sets of meteorological boundary conditions were used, one for calibration (Krähenmann et al., 2018; Rauthe et al., 2013), and one for predicting the climate change impact on yields (Brienen et al., 2020). The latter is based on regional climate simulations (EURO-CORDEX project and ReKliEsDe project). We used the six runs of the core ensemble for the Representative Concentration Pathways scenario 8.5 (RCP8.5), with an average increase in mean temperature from April to September of 1.1 ± 0.16 °C (mean ± standard error) for the Stuttgart Region from 2020 to 2050.

For management, we derived sowing and harvest dates from the

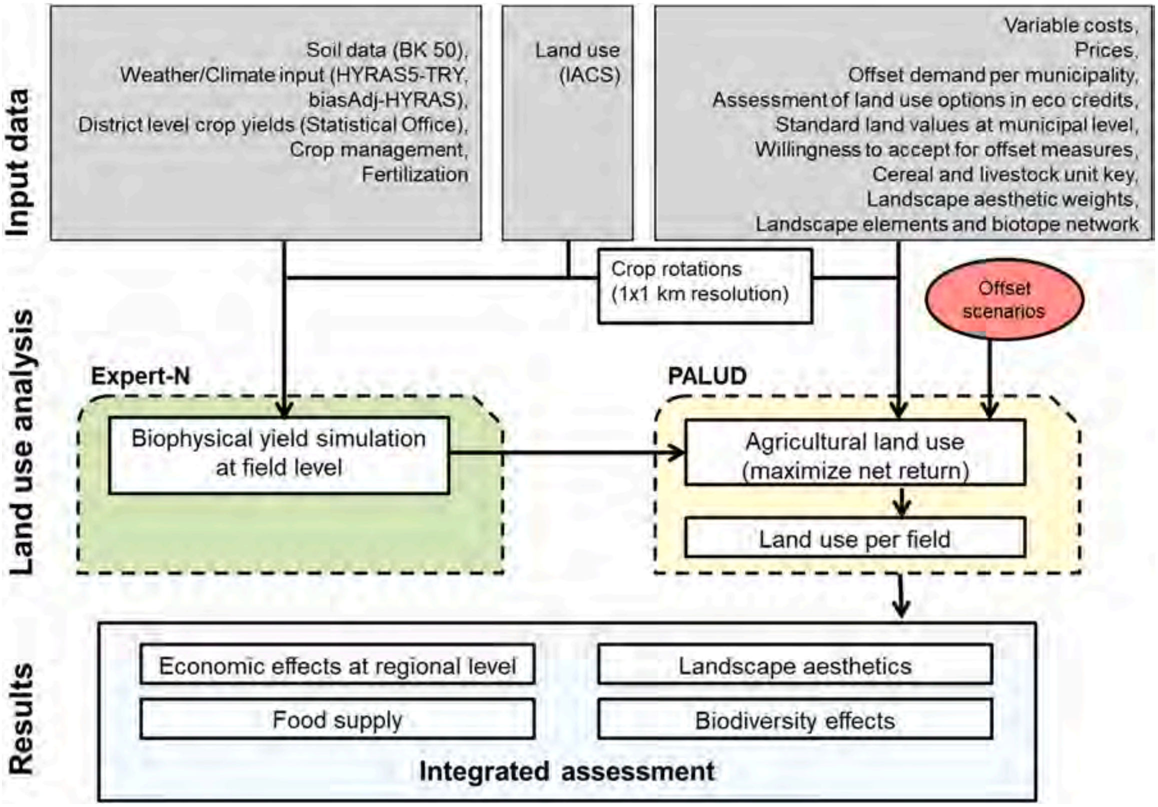

Fig. 3. Diagram of the modelling framework with the linked Expert-N and PALUD models and their respective input and output data.

phenology data of the German Weather Service (DWD Climate Data Center, 2019) for the time period 1995–2019 and extrapolated them into the future. Mineral and organic N fertiliser were applied as indicated in Table A1 (Appendix A).

Crop model parameters were estimated for each crop type in two steps. First, we optimised phenological parameters. Then, we adjusted parameters of the plant growth model by matching simulated crop yield to publicly available yield data (Stat. Landesamt BW, 2020a), which are based on farm surveys and aggregated to district level. We used bias, mean error and root mean square error as the indicators for model performance in the calibration procedure. The highest priority was given to reducing bias. When using the calibrated parameter sets of the calibration subset in the full setup (3500 simulated response units), the bias was less than 10% for all crops. Crop yields were predicted for the period 2020–2050 using the calibrated model, sowing and harvest dates as well as fertilisation as outlined above. Fig. 4 shows the development of the average yields of the seven selected crops in the Stuttgart Region under RCP8.5 until 2050. We found winter wheat yields to decrease by around 11% between 2020 and 2050, corresponding to a temperature increase of 1 °C. This finding is close to the study of Asseng et al. (2015), who predicted a decrease of between 3% and 7% per °C temperature increase.

For grain maize, Bassu et al. (2014) found a decrease of 5 decitonnes per hectare per °C temperature increase, whereas our study showed a decrease of about 2.3 decitonnes per hectare or 3% per °C. For spring barley we found a decrease of 4% per °C temperature increase which is

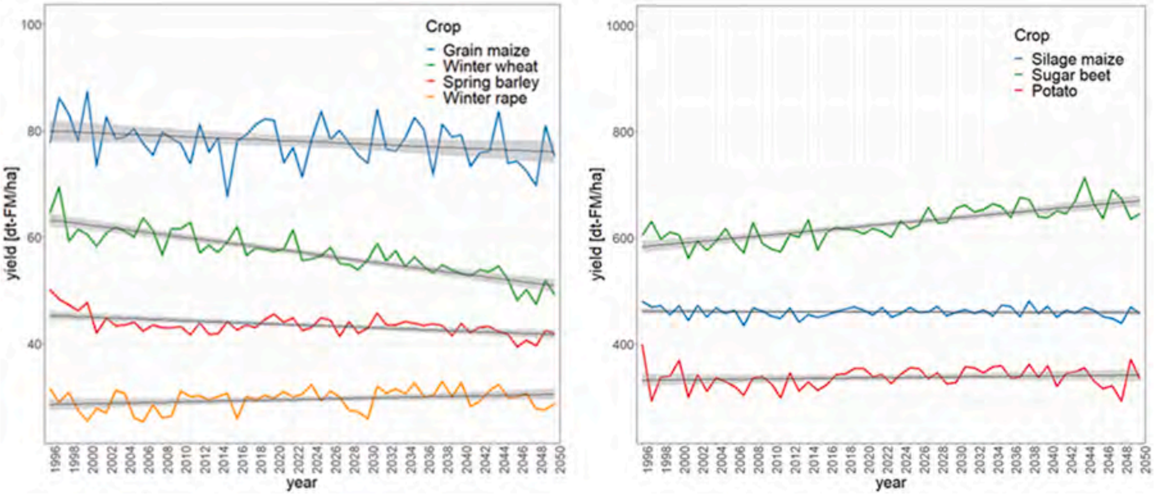

Fig. 4. Development of the predicted mean yield (decitonnes fresh mass (dt FM) per ha) in the Stuttgart Region for the seven selected crops under RCP scenario 8.5.

in the range of the findings of Tao et al. (2020) with strongly diverging yields between different models, most of them predicting yield decrease of between 0% and 20% for two locations in Europe. Annex A gives a more detailed description of the crop growth modelling approach.

The simulated yields were then averaged to obtain a robust mean yield for the period 2020–2050, and used for the economic assessment of the agricultural activities described below. Frequently grown winter wheat served as an indicator of the relative yield capacity of a field site for other winter cereals such as winter barley. For this purpose, the yields were set in relation to the average yield in Baden-Württemberg between 2013 and 2018 (Stat. Landesamt BW, 2020a). Hence, the crops covered by the Expert-N simulation accounted for more than 80% of the arable land. For the remaining crops, three different yield levels were assumed depending on soil quality. This is explained in more detail in the following paragraph (see also Table 4).

The calculation of the gross margins (GMs) took into account the field-specific yields and also drew on economic standard calculation data, price statistics (AMI, 2018, 2019, 2020; KTBL, 2010, 2019a, 2019b, 2019c; LEL, 2018a, 2018b; LfL, 2019) and individual publications (AWI, 2019; LFULG, 2006). In terms of costs for all crops and crops not covered by the crop growth model, a distinction was made between three intensity levels. They are based on the level of natural soil fertility from the BK 50 in Baden-Württemberg (LGRB, 2015) (value level 3–4 high, 2–2.5 medium and 0–1.5 low). The transformation value of arable forage crops via animal use was valued at 0.21 €/10 MJ NEL (net energy content for lactation) depending on GJ or MJ NEL content, based on the price of maize silage. All prices and costs are net amounts from a value added tax perspective.

Due to different crop rotations and yield capacities of the fields in the region, the average gross margins varied considerably between the districts. The average gross margins were particularly high in the Stuttgart urban district due to the high proportion of high value-added specialty crops. In addition, the standard land values (BRWs) which served as information on land prices were comparatively high as well (Table 2).

As an alternative to regular crop rotations, the field plots could now be used for the implementation of biodiversity offset measures. Offset measures were implemented permanently, but the proceeds for the eco credits accrued to the farmer at the beginning of the measure. In order to ensure comparability between arable land use and an offset measure from an economic point of view, the respective net present values were calculated. The GMs of the crop rotations were then capitalised using the perpetuity formula and an interest rate of 2% in line with the compensation guidelines for agriculture (Land R 19 – Entschädigungsrichtlinie Landwirtschaft). The offset measures, their implementation criteria and the associated net present values are described in detail in the following section.

3.1.3. *Selecting and incorporating offset measures in the model*

We first discussed ecological effectiveness with eight relevant stakeholder groups in and outside the region (i.e. the department for environmental protection of Stuttgart with its soil and species protection unit, the real estate and housing office representing the interests of agriculture in Stuttgart, the local nature conservation authority of the Rems-Murr-Kreis, NABU (a non-governmental organisation active in nature conservation), the regional planning association (Verband Region Stuttgart), Flächenagentur Baden-Württemberg (eco credits broker) and the cultural land foundation of Rhineland-Palatine). We then selected five typical biodiversity offset measures for consideration in the model: perennial flowering (on the entire field plot or strips), species-rich wildflower field as a variation of a perennial flowering on lean sites, fallow land, extensively used arable land, and the conversion of arable land into grassland. This is because the stakeholders' assessment using a Likert-scale (see Appendix C) showed that these measures tend to enjoy broad support compared to others, for instance, short rotation plantation. In addition, the offset measures in Appendix C were also partially aggregated, for instance extensively used arable land and double seed row spacing, as these can complement each other well in practice (Etterer et al., 2020).

In the model, offset measures could be implemented on each plot as an alternative to arable use in the status quo. Each measure was associated with certain costs, revenues and a risk premium or WTA. We used the WTA estimates for different offset measures and the land register entry provided by Sponagel et al. (2021). These estimates were mainly derived from farmers in Baden-Württemberg and the Stuttgart Region. In addition, a different number of eco credits could be generated with each measure. The evaluation of this enhancement potential was previously carried out by the Flächenagentur Baden-Württemberg (www.flaechenagentur-bw.de/) as a qualified service provider in the field of landscape planning and brokerage of offset measures for compensation obligated parties and provided for the study. Depending on site-specific conditions such as soil quality, the expected target habitat type for a measure may vary as shown in Fig. 5. Therefore, each measure was divided into a maximum of six levels in terms of assessment in eco credits based on the soil parameters "natural soil fertility" and "special site for semi-natural vegetation" from the BK 50 in Baden-Württemberg (LGRB, 2015). The "special site for semi-natural vegetation" parameter is essentially derived from the water balance, the soil depth and the nutrient supply at the specific location. Consequently, these locations are rather extreme sites, for instance, particularly wet or dry areas on which specialised species can develop (LUBW, 2010). This constitutes a kind of potential development and does not mean that semi-natural vegetation is present at these sites (LUBW, 2010). Especially when converting arable land into grassland, the nutrient supply is of particular relevance for the composition of the potential future species. This is depicted more particularly by the parameter "natural soil fertility" (Ceulemans et al., 2011). This leads to the "grassland" measure being rated higher on field 1 than on field 2 in terms of eco credits.

The willingness to accept directly depended on the standard land value or estimated market price for arable land. This means that the possible reduction of the market value is included in the WTA (Sponagel et al., 2021). The BRWs were provided at the municipal level by the respective expert committees and were collected online. Values were available for about 60% of the municipalities, mostly from 2018.

Table 2

Key figures on the structure of agriculture in the individual districts in the Stuttgart Region.

Urban/rural district	UAA[a] in ha	Share of ARA[b] [%]	Share of cereals in crop rotation [%]	Share of specialty crops on ARA [%]	Mean BRW[c] for arable land [€/m^2]	Mean gross margins per ha between 2015 and 2019 [€]
Böblingen	22,275	66.4	62.2	1.4	4.71	716
Esslingen	19,488	49.7	62.4	9.0	6.52	1537
Göppingen	27,742	43.3	62.3	0.2	3.15	630
Ludwigsburg	31,011	75.6	63.9	2.4	3.90	902
Rems-Murr-Kreis	25,125	44.4	61.4	3.1	4.47	1157
Stuttgart	2383	55.8	55.3	9.9	15.97	2121

[a] Utilised agricultural area.

[b] Arable land.

[c] Standard land value.

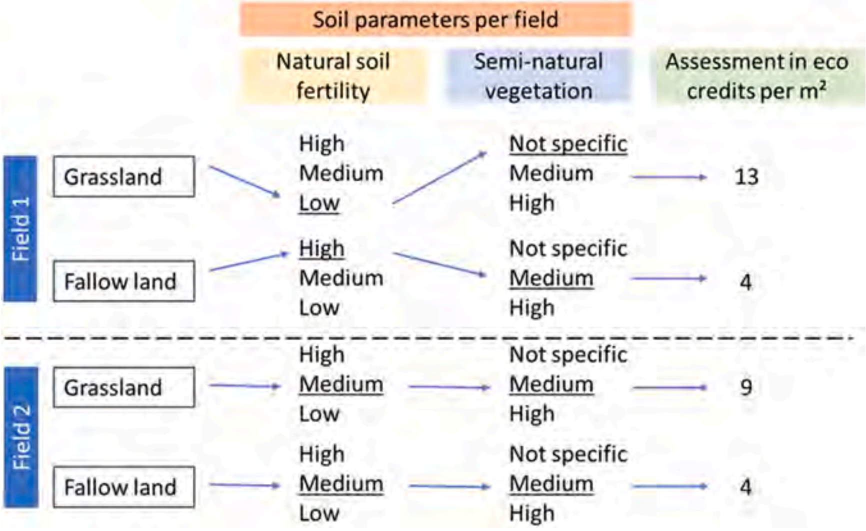

Fig. 5. Diagram of the evaluation procedure of the offset measures in the model.

Missing values were added by spatial interpolation by Inverse Distance Weighting using the "idw" function from the "phylin" R package (R Core Team, 2019; Tarosso et al., 2015). Furthermore, the WTA included a fixed amount for the land register entry and referred to both the type of measure and the loss of yield dependent on the area occupied by the measure.

Table 3 gives an overview of the selected measures, the incorporation in the model with improvement in eco credits, the net present value per ha with regard to the WTA and the capitalised GM of the reference crop rotation system (M0). These net present values also included one-off transaction costs, for instance approval of the measure by the local nature conservation authority and sale of the eco credits, which were estimated uniformly for all measures at € 2440 per ha (Etterer et al., 2020). When calculating the costs, it was assumed that the maintenance period is limited to 25 years (Fellenberg, 2016). After that, an area is still a compensation site. However, no active action can normally be required by the farmer later on. Due to other legal obligations, there is nevertheless an obligation for minimum maintenance that is, for instance, specified in agriculture and landscape management legislation in Baden-Württemberg (*LLG*). We assumed this takes effect after 25 years. This reflects the approach of a rational farmer who minimises the costs of the measure.

Table 3
Overview of the selected offset measures and incorporation into the model in relation to the reference crop system with the WTA based on Sponagel et al. (2021).

Measure	Description	Improvement in eco credits on ARA per m^2	WTA in € per ha	Net present value in € per ha
M0	Reference (REF)	0	0	NPV$_{M0}$
M1	Perennial flowering	8	71,629 + 1874*BRW[a]	-6083 – WTA
M2	Species-rich wildflower field	4–18	71,629 + 1874*BRW[a]	-7971 – WTA
M3	Fallow land	4	71,629 + 1874*BRW[a]	-4463 – WTA
M4	Extensive used arable land with cereals	4–15	58,644 + 1874*BRW[a]	[– 6027; 7306] – WTA
M5	Conversion into grassland	9–17	73,830 + 1874*BRW[a]	[695; 2562] – WTA

[a] BRW: standard land value per € per m^2.

M0 corresponds to the status quo, i.e. a reference crop rotation system (REF) was maintained. There was no improvement in terms of eco credits and the net present values of the average GMs were calculated as described in Section 3.1.2. M0 can refer to more than one reference system, and this is explained below.

M1 corresponded to the establishment of a perennial flowering area on the entire, 10% or 30% of the field. Native seed was used, and reseeding took place every 5 years. In comparison to agricultural use, this led to an improvement of 8 eco credits per m^2 at all sites. The annual costs within the first 25 years amounted to € 135 per ha and led to € 2637 per ha in capitalised terms (KTBL, 2019b; Rieger-Hofmann, 2021). After 25 years, only minimum annual maintenance takes place. This was set at € 33 per ha (KTBL, 2019b) and year and capitalised for eternity. All in all, the net present value of the measure was € − 6083 per ha, including the transaction costs.

M2 addressed the establishment of a species-rich flowering field with native seeds. Major enhancement in terms of nature conservation can be expected, particularly, on lean sites. In comparison to agricultural use, this led to an improvement between 4 and 18 eco credits per m^2. The implementation costs with seed were estimated at € 3881, followed by annual costs of € 33 for cutting (KTBL, 2019b; Rieger-Hofmann, 2021). This led to a net present value of € − 7971, including transaction costs.

M3 corresponded to fallow land and led to an improvement of 4 eco credits per ha at all sites. The field was permanently fallow and € 51 per ha (LfL, 2019) was set for a one-off annual minimum cultivation, i.e. tillage and cutting. After 25 years the cultivation could be reduced to cutting and set at € 33 per ha (KTBL, 2019b) and year. Hence, the net present value of the measure was € − 5107 per ha, including transaction costs.

The M4 measure corresponded to extensively used arable land. No pesticides were used and N fertilisation was reduced to up to 50% of the requirement for the crop at half the sowing rate (Gödeke et al., 2014). In addition, mechanical weed control was only feasible to a very limited degree. Consequently, the cultivation of root crops was not appropriate at all under these circumstances. Hence, four crop rotations of rye, spring barley, wheat and oat were possible in the model (Jeangros and Courvoisier, 2019; Meyer and Leuschner, 2015). In addition, a 70% yield loss was assumed compared to crop cultivation under M0 (Geisbauer and Hampicke, 2012). This led to an improvement of between four and 15 eco credits per m^2. The annual GMs were between € − 72 and € 19 per ha (LfL, 2019).

M5 corresponded to the conversion of arable land into grassland, leading to an improvement of between 9 and 17 eco credits per m^2. The grassland was extensively managed, i.e. one cut per year. Organic grassland yields were then assumed of between 24.9 and 33.9 dt dry matter (DM) or 1319.7 to 1797.7 10 MJ NEL per ha (LfL, 2019), depending on the three mentioned natural soil fertility value levels of the BK 50. The price per dt DM was set at € 13, which led to positive net present values between € 1091 and € 3017 (LfL, 2019; Rieger-Hofmann, 2021). This also included the one-off costs to establish grassland, i.e. seed, tillage and sowing in the first year, and transaction costs.

Payments from the first pillar of the Common Agricultural Policy (CAP) were not considered in the analysis, as it can be assumed that is was still possible to apply all M0 to M5 measures. This is because, according to European Court of Justice (ECJ) (2010), the conditions for receiving direct payments from the first pillar of the CAP were also met if predominantly nature conservation objectives were pursued. In all cases, we assumed that the land would be maintained in good agricultural and ecological condition and that minimum annual management would be carried out in accordance with Section 2 *DirektZahlDurchV* (Regulation on the implementation of direct payments).

3.1.4. *Land use optimisation with PALUD*

PALUD is a field-specific optimisation model based on linear programming. On the basis of the IACS dataset, crop rotations specific to each field were derived using the sequence of crops for the period 2015–2019. The Stuttgart Region was, therefore, divided into 3037 1 × 1 km^2 pixels. As a reference crop rotation system (M0), all existing crop rotations in a pixel were available for a field within this pixel. This led to an average of 16 available crop rotations per pixel, and was intended to anticipate the individual site conditions and agricultural structural framework conditions. Moreover, the M1 to M5 offset measures were available on all field plots. Hence, on average there were 21 land use options available per field plot, including five offset measures.

In the model's objective function, the net present value of agricultural use across the region (77,698 field plots) was maximised, subject to certain constraints, in order to keep the model within reasonable boundaries. This included assumptions of arable forage requirements for livestock, biomass for biogas plants and restrictions on the utilisation of biomass from extensive grassland for fodder or biogas (M5 offset measure). In addition, it was assumed that the cropping area for fodder cereals had to make up at least 60% of the volume in the status quo in order to take into account the requirements of livestock farming (BLE, 2020a). With a view to anticipating the adaptation possibilities of agriculture to future production conditions, the amount of each crop in ha in the optimal solution of the model was increased by a maximum of 25% per municipality or by a maximum of 20% in the entire region.

In the first model run without any offsetting requirements, the total net present value was calculated for the entire region and for each municipality. Then, the fulfilment of the offsetting requirement, i.e. a certain number of eco credits in the respective scenario according to Table 2 within the region, per municipality (if the municipality has more than 105 ha of arable land) or within the search area map, was introduced as a restriction in the model. The total number of generated eco credits per field resulted from the product of the occupied area of a land use option and the respective assessment in eco credits of the option on the field. A more detailed description of the modelling approach is given in Annex B.

3.2. *Integrated assessment*

3.2.1. *Economic effects at regional level*

Compared to a situation without any demand for eco credit, the net present value of agricultural land use was reduced by the implementation of offset measures. Hence, the average price per eco credit was calculated by dividing the difference in capital values by the number of eco credits generated.

3.2.2. *Food supply*

We used to Cereal Unit (CE) to assess the impact of biodiversity offsetting on regional food production. This is a standardised metric established in German agricultural statistics to compare the feed value of different agricultural products on the basis of their energy supply capacity, whereby 100 kg of barley corresponds to one cereal unit (BLE, 2020b; Mönking et al., 2010).

3.2.3. *Landscape aesthetics*

In general, factors such as relief or the presence of water bodies have a positive effect on landscape quality, while open and intensively used agricultural landscapes are often given a low rating (Hermes et al., 2018). Therefore, we considered both the assessment of the entire landscape in general and the agricultural landscape in particular.

First, a weighted Shannon diversity index (*wSDI*) was calculated as an indicator for the visual quality of the agricultural landscape for each pixel for all scenarios. Preference values for individual arable crops, grassland and other landscape elements were used, which were based on Schüpbach et al. (2009). For the calculation, all elements with a higher preference value than the average (e.g. extensive meadows and pastures, hedgerows, orchards, wet meadows, wildflower strips and field margins) were considered as separate landscape elements. All elements with lower preference values were combined into one element (Roesch et al., 2017; Schüpbach et al., 2016). The index could then be used in land use models to describe the visual quality of landscapes in different scenarios (Schönhart et al., 2016). We then applied this calculation of a weighted Shannon index on a grid level of 1 × 1 km^2 to arable land and grassland. For the M4 measure (extensive cereal fields), the mean of the preference values of wild flower strips and winter cereals was used as a weighting factor. For the other offset measures, comparable values were available from Schüpbach et al. (2009).

Second, the 1 × 1 km^2 pixels in the model were divided into three groups according to the state-wide landscape aesthetics assessment of Baden-Württemberg, It takes the diversity, uniqueness and beauty of landscapes into account, and consists of 11 levels from 0 to 10 (Roser, 2013, 2014). Hence, the geodata based map was intersected with the field plots to derive the average rating score for each pixel. Pixels with a rating under five were considered as below average (approximately 24%), pixels with a value of five were considered as average (approximately 49%) and pixels with value greater than six were considered as above average (approximately 27%). As a result, the *wSDI* could be displayed separately for each of the three groups. The aim here was to illustrate the extent to which upgrading takes place in areas with different baseline levels.

3.2.4. *Biodiversity effects*

In addition to assessing the ecological enhancement of the management of individual areas, for instance, in eco credits for offset measures, the impacts on biodiversity must also be considered at the landscape level (Gámez-Virués et al., 2015; Tscharntke et al., 2005). Hence, we included additional indicators for crop diversity and landscape connectivity which are important landscape metrics on biodiversity (Walz, 2011). Crop diversity was depicted by the Shannon diversity index (*SDI*) which was calculated for each pixel in the scenarios. The Shannon diversity index takes into account both the abundance and the evenness of crops present in the given region to characterise crop diversity (Spellerberg and Fedor, 2003). In this study the index was used to characterise the diversity of the agricultural landscape in terms of crop diversity based on the IACS dataset. It was calculated according to Eq. (1), taking into account the relative abundance of the crops (p_{crops}). This also included areas with offset measures.

$$SDI = -\sum_{crops} p_{crops} \ln\boxed{f0}(p_{crops}) \tag{1}$$

Furthermore, habitat connectivity was calculated as the share of arable land within less than 50 m of landscape elements or biodiversity offsets (Schönhart et al., 2011). These landscape elements included woody structures, biotopes according to the *BNatSchG* from the IACS dataset, and core areas of the wetland and dryland biotope network (ALKIS, 2018; LUBW, 2020a, 2020b).

3.3. Offsetting scenarios in the Stuttgart Region

As part of the forecast of future development trends for land use in the Stuttgart Region, biodiversity offsetting – in addition to land use for settlement and construction areas – was also identified as an essential descriptor based on expert knowledge from Jenssen (2020c). In addition, various trend alternatives for offsetting within the region were defined from which the basis for the considered scenarios was derived. Four different scenarios were, therefore, examined to cover the offset requirements in the Stuttgart Region (Table 4).

In scenario 1, spatially unrestricted offsetting could be implemented throughout the region (off-site). The entire demand for eco credits of all municipalities in the region had to be covered.

In scenario 2, it was assumed that offsetting takes place at the site of intervention (on-site). Any offset measures, therefore, had to be implemented in the respective municipal area according to the estimation of the demand for eco credits. The requirement was relaxed for municipalities with less than 105 ha of arable land, where the entire eco credit demand did not have to be covered. This avoided model infeasibility which was determined iteratively. Hence, approximately 90% of the entire eco credit demand had to be covered on-site.

In scenario 3, offsetting did not have to be implemented at the site of intervention, but measures were spatially coordinated at the regional level (off-site). In this case, at least 90% of the eco credit demand had to be covered within a defined spatial setting. For this purpose, a new search area map for biodiversity offsets was used that had been developed and provided by the *Verband Region Stuttgart*. This search area map was essentially founded on the water bodies and surrounding areas as the basis of a biotope network structure in the region. Important state-wide biotope network structures in Baden-Württemberg were also specifically addressed at local level. This promoted the strengthening of the biotope network, an important political goal (Bannas et al., 2017).

Scenario 4 was a compromise between scenario 2 und scenario 3. In comparison to scenario 2, just 75% of the offset demand had to be covered on-site, the other 25% of the required eco credits had to be generated within the search area map.

4. Results

4.1. Implementation and distribution of measures depending on the scenario assumptions

Depending on the scenario, the total arable land occupied by offset measures ranged between approximately 6415 ha and 8736 ha, respectively 8.9% and 12.1% of the total arable land. Moreover, spatial disparities between the districts were apparent. The comparison of scenario 1 and scenario 2 showed that in the case of spatially unrestricted compensation, fewer measures were implemented especially in the districts of Stuttgart, Esslingen and Ludwigsburg, but more measures in the district of Göppingen (Table 5).

Table 4
Overview of the scenarios considered for offsetting in the Stuttgart Region.

Scenario	Total number of eco credits [EC] required in millions	Coverage of the offset demand within the municipality	Additional coordination of the measures
0: No offset	0	No	No
1: Off-site	775	No	No
2: On-site	775	Yes (if arable land > 105 ha)	No
3: Off-site with coordination	775	No	Yes, > 90% of EC within the search area map
4: Partly off-site with coordination	775	Partly, 75% of EC in comparison to scenario 2	25% of EC within the search area map

Fig. 6 shows the spatial volume of the individual offset measures by scenario. The M1 measure (Perennial flowering) had the highest volume in all scenarios, followed by M2 (wildflower field), M4 (extensive arable land) and M5 (grassland). According to M4 and M5, there were no significant differences between the scenarios. In contrast, the implementation of M1 and M2 was quite sensitive to the scenario. In scenarios 2 and 3 the M2 measure had a lower volume than in scenarios 1 and 4. The opposite relationship was observed for M1.

Fig. 7 shows the spatial distribution of offset measures in the region by scenario. Overall, it could be seen that perennial flowering (M1) and wildflower fields (M2) were the predominant measures in all scenarios. Measure M2 was mainly implemented in the western part of the region, whereas M1 was more widely distributed. M4 (extensive farming) and M5 (grassland) measures were relatively evenly distributed within the region, independent of the scenario. M3 (fallow land) was not implemented at all. In scenario 1, all measures were predominantly implemented on the periphery of the region, which was farmed more extensively from the outset and had a far lower population density than the centre of the region. In contrast to the other scenarios, the M1 measure was then mainly implemented in the south and north of the region. In scenario 3, the connectivity structures of the water bodies and floodplain areas were clearly recognisable on the basis of the search area map. Additionally, in scenario 3, significantly fewer measures were implemented on the western edge of the region. The scenarios 2 and 4 were relatively comparable with regard to the location and distribution of the measures. Nevertheless, the M2 measure was implemented to a lesser degree in scenario 2.

The spatial distribution of the measures in Fig. 7 was in line with the coverage of the offset requirement per municipality (Fig. 8). In scenario 1, many municipalities in the centre of the region with a high population density generated less than 10% of the required eco credits (Table 6), whereas there were municipalities in the peripheral areas of the region with a coverage rate of more than 500%. In scenario 3 there was no longer a clear gradient between the centre and the periphery of the region. However, there were also spatial disparities between municipalities.

In the case of on-site (scenario 2) or predominantly on-site compensation (scenario 3), there were no longer any major disparities, apart from exceptions, i.e. municipalities with less than 105 ha of arable land. Nevertheless, even in these scenarios there were municipalities with a particularly high degree of coverage, especially on the western edge of the region.

4.2. Impact of the scenarios on the selected factors of the integrated assessment

Table 7 gives an overview of the economic indicators of the scenarios for offsetting as well as the impacts on the regional food supply. The implementation of offset measures in a spatially unrestricted area (scenario 1) led to the lowest total costs and the lowest decline in food supply in CE. In contrast, restricting the potential implementation area for offsets to the area of the search area map led to higher costs of 39% compared to scenario 1 and higher impacts on regional food supply. The results for scenarios 1 and 4 were quite close, regarding total costs and implications for food production. Furthermore, there was rather low model sensitivity to changes in producer prices for crops and average prices per eco credit in the scenarios. A price change of 20% in producer prices, increased averages prices per eco credit by about 12%. The relative price differences between the scenarios were quite robust. Assuming a higher interest rate led to lower necessary prices per eco credit, a lower interest rate would necessarily lead to higher ones. In

Table 5
Overview of the implementation of offset measures on arable land by district and scenario.

District	Implementation areas of offset measures on arable land in 1000 ha by scenario				Area covered by offset measures in relation to ARA in scenario in %			
	1. Off-site	2. On-site	3. Off-site with coordination	4. Partly off-site with coordination	1. Off-site	2. On-site	3. Off-site with coordination	4. Partly off-site with coordination
Böblingen	1.63	1.75	2.12	2.02	11.0	11.8	14.3	13.6
Esslingen	0.59	1.45	1.41	1.12	6.1	15.0	14.6	11.5
Göppingen	1.46	1.05	1.15	0.79	12.2	8.8	9.6	6.6
Ludwigsburg	1.67	2.00	2.55	1.75	7.1	8.5	10.9	7.5
Rems-Murr-Kreis	1.06	1.26	1.33	0.93	9.5	11.3	11.9	8.3
Stuttgart	0.00	0.05	0.18	0.03	0.3	3.5	13.3	2.5
Stuttgart Region	**6.41**	**7.56**	**8.74**	**6.64**	**8.9**	**10.4**	**12.1**	**9.2**

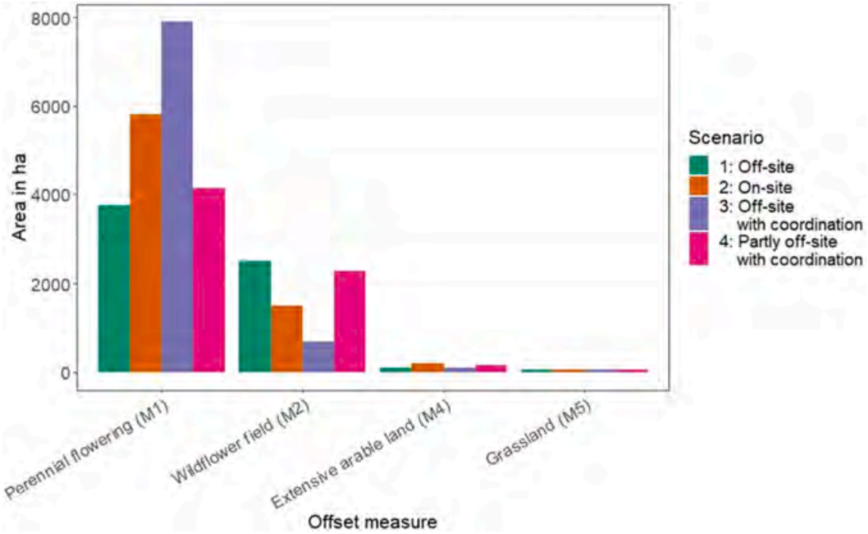

Fig. 6. Spatial volume of the individual offset measures by scenario.

comparison, the costs between the scenarios also remained relatively stable.

Fig. 9 shows the impacts on landscape aesthetics by means of the differential change in the Shannon Index with scenario, for the three different landscape quality categories. Overall, this demonstrated that biodiversity offsets tended to lead to an improvement in visual landscape quality, in general. However, the potential for enhancement also depended on the initial condition. In addition, a certain tendency for a correlation between the general landscape quality and the aesthetic assessment of the agricultural landscape could be observed in Fig. 9. Nevertheless, the overall variation was quite high. In areas that already had high landscape quality, there hardly seemed to be any variations between the scenarios in terms of enhancement, although the volume of measures differed between the scenarios in this area. Especially in the case of on-site compensation (scenario 2), a comparatively high degree of enhancement could be achieved in areas with low landscape quality, whereas in scenario 1 there was a considerably less enhancement in this area. However, only minor differences between scenario 2 and 4 were visible, i.e. 100% or 75% on-site offsetting.

Table 8 shows the spatial distribution of the offset sites among the categories of general landscape quality. Most of the measures were implemented in areas with average landscape quality. However, there were disparities between the scenarios regarding areas below and above average. Whereas in scenarios 1 and 3 about 8% of the measures were implemented in areas with low landscape quality, in scenario 2 there were almost twice as many measures implemented in such areas.

Fig. 10 gives the indicators related to biodiversity effects. The implementation of the offset measures did generally improve habitat connectivity. Whereas in the baseline condition about 33% of the arable land was within a 50 m radius of landscape elements, this value increased to about 44% in scenario 2, including the offsetting sites as new connectivity structures. In this respect, too, on-site compensation showed the greatest potential enhancement (Fig. 10a). With regard to the Shannon diversity index (*SDI*), no differences could actually be observed from offsetting on arable land between the scenarios, although there did seem to be a very slight decrease in scenario 3 (see Fig. 10b).

5. Discussion

The discussion consists of several parts. First, we discussed the model results in terms of our research questions and contribution to the literature. Second, we discussed the model evaluation with a focus on challenges, assumptions and uncertainties. Finally, we focused on the contribution of biodiversity offsets to sustainable agriculture in general.

5.1. Model results and contribution to the literature

In principle, any form of land sealing should initially be avoided in the interest of nature conservation. However, reality shows that this is not or hardly possible. Against this backdrop, an approach to nature conservation compensation should be chosen that results in optimisation from an ecological, social and economic perspective. In this context, our analysis using the example of the Stuttgart Region showed that there was a major potential for offsetting on arable land. However, we also identified spatial disparities in terms of the most cost-effective measures. The application of a free market principle without further spatial

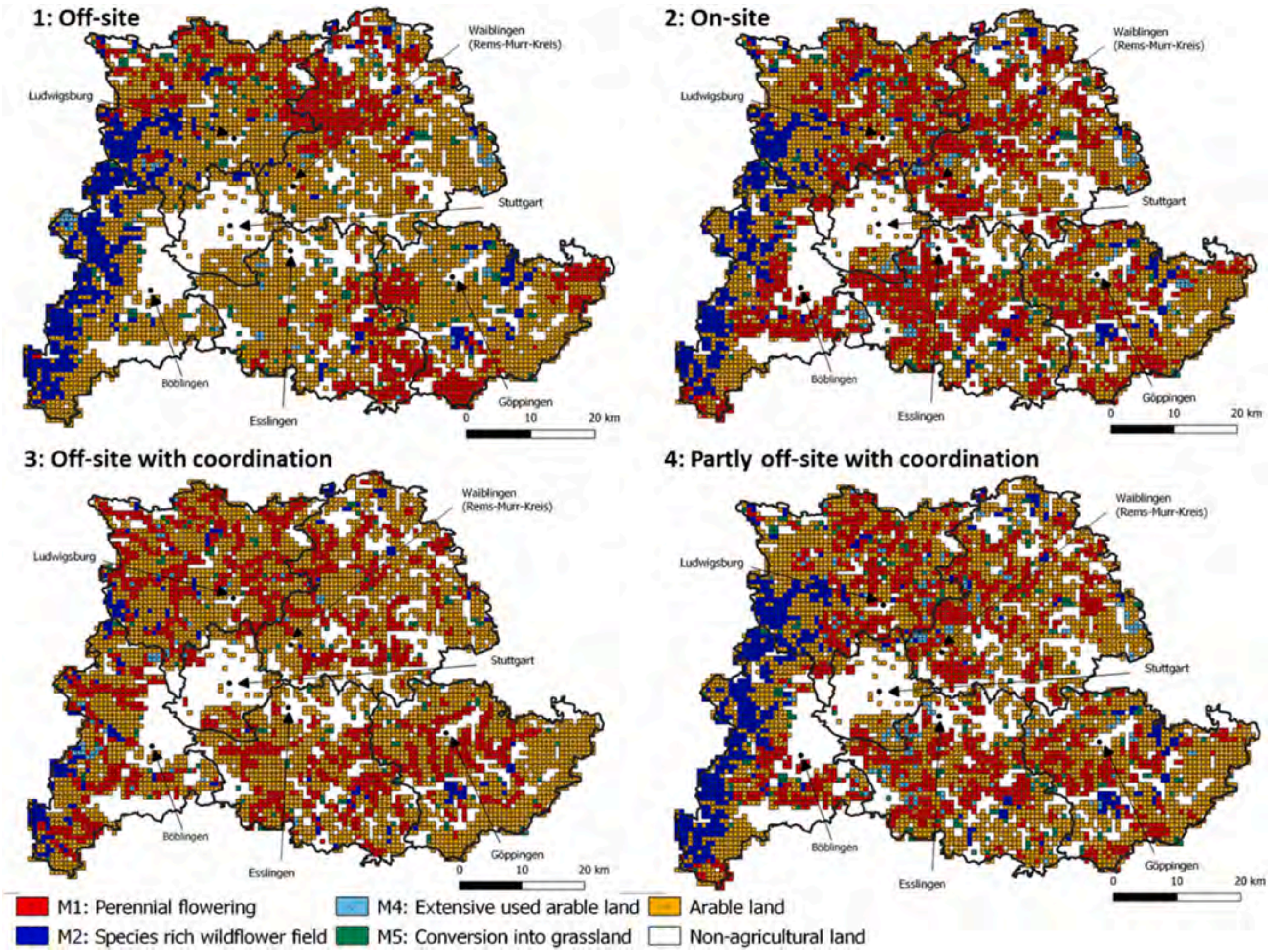

Fig. 7. Spatial distribution of the compensation measures in the region on a grid level of 50 ha showing the measure with the largest area in each grid (ALKIS, 2018; BKG, 2018).

restrictions for offset sites resulted in the lowest total cost for offsetting. In this scenario, most of the measures would be implemented on the periphery of the region. In contrast, implementation of offset measures in a highly restricted area, for instance using the search area map led to the comparatively highest costs. Due to the strong spatial restriction, flexibility with regard to the choice of location for the measures was limited. Land with high standard land values and high potential value creation also had to be used for compensation. In general, the identified regional disparities could be explained firstly by the yield capacity of the land and secondly by the standard land values. Particularly, in the Stuttgart district, the standard land values for arable land were up to € 16 per m^2. At the same time, there was a high proportion of specialty crops with comparatively high gross margins. Hence, in response to research question R1 we found that agriculture in metropolitan regions could still provide offsetting sites. However, this was heavily dependent on monetary compensation. Thus, we also demonstrated that spatial planning, for instance on-site or off-site, had a major impact on the compensation costs, which relates to R2.

Furthermore, the results of the scenarios differed with regard to landscape aesthetics and other ecological indicators. Under free market conditions or off-site compensation (scenario 1), measures were more likely to be implemented in areas with already high visual landscape quality, i.e. the potential enhancement was lower. Hardly any measures would be implemented in the centre of the region although about 22% of the region's population, who benefit from landscape attractiveness, live in the city of Stuttgart (Stat. Landesamt BW, 2021). This relates to R3 whereby a spatially unrestricted market mechanism for offset measures might lead to polarisation in terms of ecological and cultural landscape quality between urban and rural areas or between intervention and compensation areas. We agree with Grimm and Köppel (2019) that on-site compensation might avoid the reallocation of ecological values to rural areas. In this context, our results also supported the findings of Gonçalves et al. (2015), that off-site compensation might not always be desirable with regard to benefits for the local community. Consequently, the potential additional costs for on-site compensation also have to be considered from this point of view (Jones et al., 2019).

Due to the offset obligations, no actual differences between the respective scenarios were observed in terms of the Shannon diversity index. The index was used as an indicator for intensification of farming, for instance diversity of crop rotations. In this context, the use of production inputs, such as plant protection products would still have to be taken into account (Levers et al., 2016). With regard to landscape or habitat connectivity, we observed the greatest improvement under on-site compensation in scenario 2.

In response to research question R4, we found, that additional benefits for nature conservation and visual landscape quality beyond the legal obligations could be achieved with on-site compensation approaches. These findings are in line with other studies that identified trade-offs between ecological and economic optimisation in terms of biodiversity offsets, for instance van Teeffelen et al. (2014).

Besides the economic impacts there were also disparities between the scenarios in terms of regional food supply, in response to R5. Under

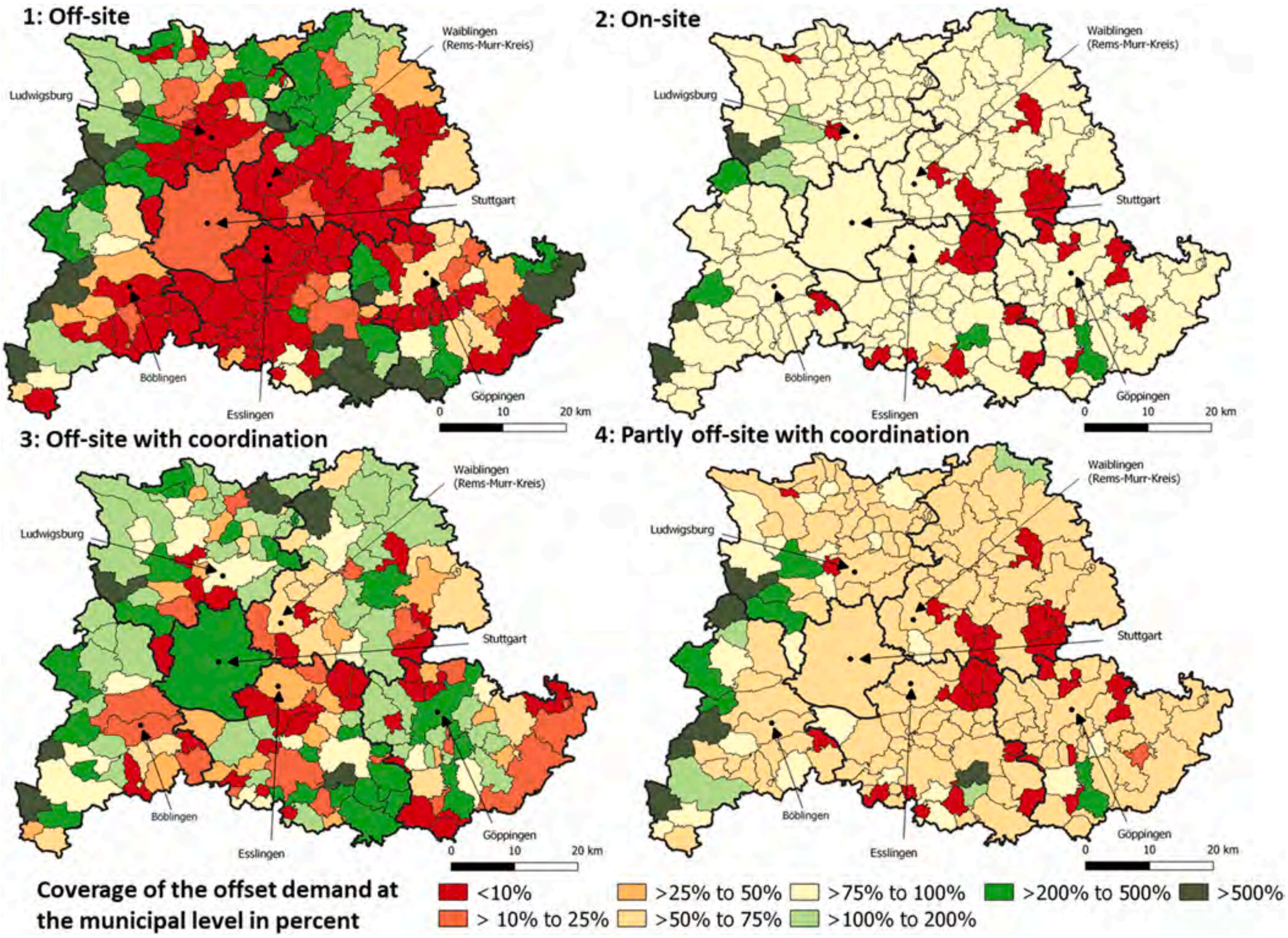

Fig. 8. Coverage of the offset demand at the municipal level in percent in the scenarios (ALKIS, 2018; BKG, 2018).

Table 6
Coverage of the offset demand in scenario 1 in the five municipalities with the highest population density in the Stuttgart Region (Jenssen, 2020a; Stat. Landesamt BW, 2021).

Municipality	Population density in people per km^2	Standard land value (BRW) in € per m^2	Eco credit demand in millions	Coverage of the offset demand in % in scenario 1
Stuttgart	3067	16	5	10.5
Asperg	2329	3.3	3.2	8.7
Kornwestheim	2309	4.9	10.9	0.4
Esslingen	2028	15	6.8	0.3
Fellbach	1648	13.9	9.2	0.7

scenario 1, regional food supply in cereal units decreased by about 6.4%, whereas on-site compensation led to a higher decline of approximately 8.0%. Mention should be made to the fact that the decline of food production referred solely to the decrease in productivity due to compensation. The potential loss of land to urban development on agricultural land was not taken into account here. From a regional food supply perspective, spatially flexible compensation would therefore be preferable, irrespective of the intervention site. In this case, the sites with the highest nature conservation suitability, i.e. the greatest enhancement potential coupled with the lowest yield potential from an agricultural perspective, could be used. But with regard to the decline in food supply, the level of supply in the status quo must also be considered. Assuming an annual per capita consumption of 12 cereal units, the demand of about 500,000 people was met based on the calculation in scenario 0 (Schönleber, 2009). This would correspond to a self-sufficiency rate of just under 20% (Stat. Landesamt BW, 2021). Although grassland, orchards and vineyards were not taken into account for the calculation, the supply rate was relatively low (Hübner and Winterling, 2020). Depending on the scenario, between 30,000 and 50,000 fewer people could be supplied, requiring compensation by imports. In this case, possible leakage effects should be borne in mind (Röder et al., 2021).

Exports of agricultural products are one driver of global biodiversity loss, depending on the crop and the region of origin (Chaudhary and Kastner, 2016). For instance, international trade in soybeans has a greater impact on global species loss than wheat (Kastner et al., 2021). Importing food can, therefore, also help to save land under certain circumstances, for instance, by concentrating grain production in North America (Kastner et al., 2021). Hence, quantifying biodiversity loss caused by the increasing demand for food imports presented quite a challenge. The figures presented here can only provide an initial overview, since self-sufficiency would, in fact, require a further breakdown by product groups and differentiation by food consumption trends (Schönleber, 2009). Assuming consumption of 9 cereal units due to decreasing consumption of livestock food (Schönleber, 2009), the food supply could be kept at a comparable level despite the implementation of offsetting measures. Although food production is declining, the impact on local natural diversity in the agricultural landscape must be addressed in the scenarios. Last but not least, this could also have long-term positive effects on crop production, which have not been taken into account here (Rosa-Schleich et al., 2019).

Table 7
Results for economic and food supply valuation in the scenarios.

Indicator	Unit	Scenario			
		1 Off-site	2 On-site	3 Off-site with coordination	4 Partly off-site with coordination
Average price per EC[a]	EURO [€]	0.68	0.82	0.95	0.74
Price change in relation to scenario 1	%	0	20.8	39.0	8.3
Total costs for offsetting	€ 1 million	528.7	638.8	735.0	572.6
Change in food production relative to Scenario 0	CE[b] in %	-6.4	-8.0	-9.6	-7.0
Average price per EC with a + 20% change in producer prices	€	0.76	0.92	1.07	0.82
Average price per EC with an interest rate of 1%	€	1.36	1.64	1.88	1.47
Average price per EC with an interest rate of 3%	€	0.46	0.55	0.64	0.50

[a] Eco credit.
[b] Cereal Unit.

5.2. Discussion of the applied modelling approach and related uncertainties

The spatially explicit PALUD model enables land use optimisation with a high resolution at field level (Agarwal et al., 2002) in combination with the Expert-N model, which simulates crop yields at the same scale as well. Therefore, we were also able to derive landscape aesthetic values and biodiversity effects for decision-making purpose. In addition, the model framework could be extended with other upstream and downstream model approaches in the future.

However, the results must be interpreted against the backdrop of the methodology and limitations of the modelling approach. In this context, the application of modelling approaches is always associated with uncertainties (Haß et al., 2020). For reasons of transparency and confidence in the model results, uncertainties should be systematically addressed, i.e. the individual evaluation of individual models, but also uncertainties that may arise from model linkages (Gabbert et al., 2010; Kirchner et al., 2021). We, therefore, engaged in critical reflection on our modelling approach according to Kirchner et al. (2021). They provide an uncertainty framework based on four major locations where uncertainties might appear and on types of uncertainties, i. e. how they can be expressed.

5.2.1. Limitations and uncertainties of PALUD

We began by focussing on the respective system boundaries and system resolution of PALUD. The PALUD model does not take into account any economic sectors other than agriculture and consequently no interactions could be considered. Furthermore, the farm-level was not explicitly represented in PALUD. To assess the profitability of the offset measures we used gross margins of the crop rotations in combination with a WTA as a risk surplus and as an indicator for the potential market value loss of the land. The structure of fixed costs and factor endowment of the farms, i.e. machine inventory and labour availability, were not taken into account. Assuming that farms only used a subordinate part of the total farm area for compensation, the influence on fixed costs was probably small. Nevertheless, the implementation of offset measures on farm level might generate time saving labour effects However, the monetary assessment of these effects would also very much depend on the individual opportunity costs (Geisbauer and Hampicke, 2012). Additionally, livestock and biogas production were included in a

Table 8
Distribution of the offset sites among the categories of general landscape quality.

Scenario	Share of total offset area in % in landscape quality category		
	Below average	Average	Above average
1: Off-site	8.3	70.2	21.5
2: On-site	15.0	66.8	18.2
3: Off-site with coordination	8.2	62.7	29.1
4: Partly off-site with coordination	13.5	66.6	19.9

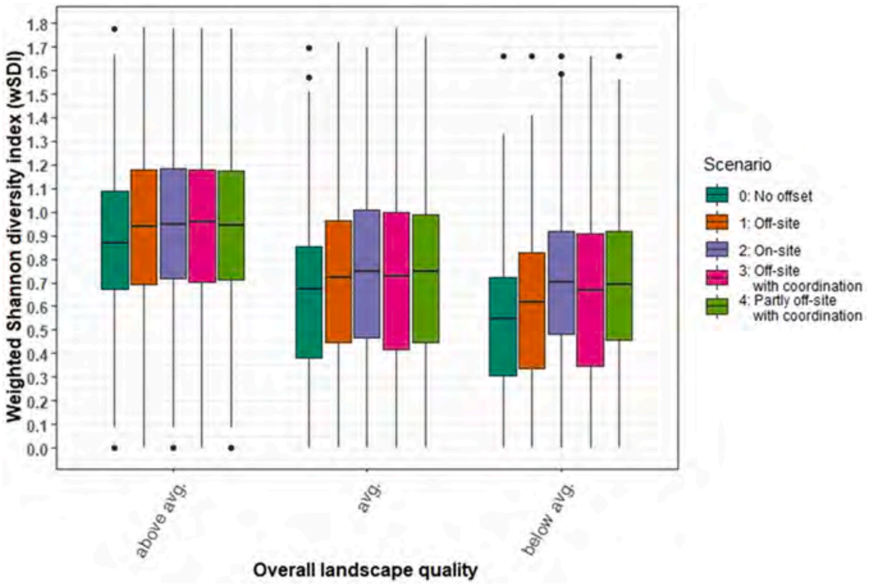

Fig. 9. Boxplots with the median of the weighted Shannon diversity index (wSDI) at pixel level for visual landscape quality of the agricultural landscape by overall landscape quality.

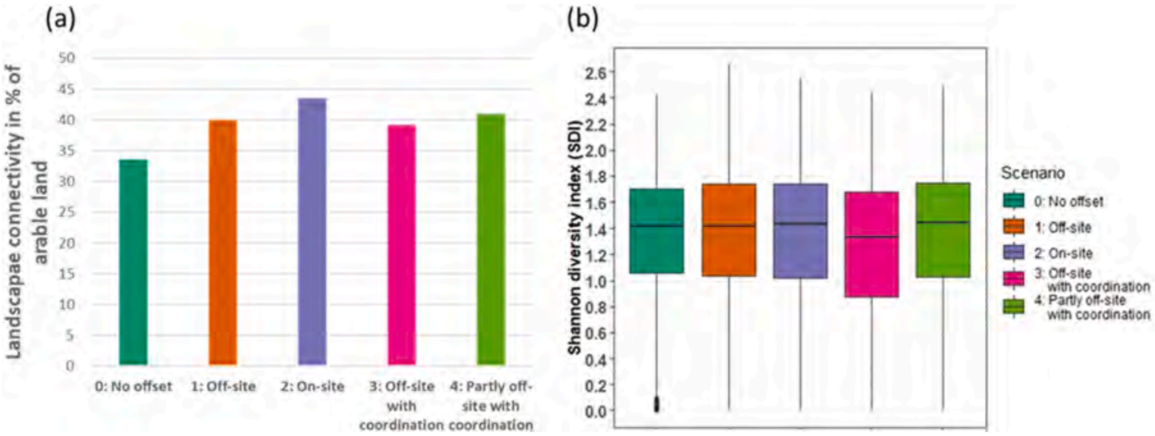

Fig. 10. Biodiversity related effects in the offset scenarios. (a) Landscape connectivity in % of arable land by scenario. (b) Boxplots for the Shannon index at pixel level by scenario with median.

simplified manner and the availability of crop rotations was used to somehow reflect the farm distributions. With regard to temporal resolution, there was just one decision-making point, which means that crop rotations per plot could not be adjusted after certain time steps.

On the input side, PALUD uses crop yields simulated by Expert-N which are also affected by uncertainties (Section 5.2.2). In addition, all prices and costs are endogenous. Consequently, potential future changes on the demand side for agricultural products and resulting price changes were not taken into account. However, we did include a sensitivity analysis of changes in producer prices in order to accommodate this kind of uncertainty. In addition, we conducted a sensitivity analysis of the interest rate used for capitalisation, which is important due to the temporal dimension. In this context, we were able to evaluate two major sources of uncertainty in our approach and found that at least the results of the different scenarios remained relatively stable in relation to each other. Potential system drivers such the Common Agricultural Policy or technological innovations, where knowledge about future development is lacking, were another relevant source of uncertainty (Haß et al., 2020).

Moreover, the model itself was one source of uncertainty. The model was calibrated using land use data from the IACS. The crop rotations were derived from the IACS dataset. Although, the IACS dataset can be considered as one of the best available agricultural land use datasets for the study region, there might still be some uncertainties due to the non-representation of field plots or other faults in the data inter alia. In PALUD a flexible adjustment of future land use compared to the status quo of 20% at the regional level and 25% at the municipal level was assumed. We anticipated the future demand for crops and other restrictions such as the local factor endowment of the farms or suitability of the land for certain crops. The assumption of a greater flexibility could lead to higher opportunity costs and, by extension, to rising prices for offsetting.

All in all, it has to be said that future projections are always uncertain (Haß et al., 2020). The model structure and decision rules were, therefore, constructed to keep the model within reasonable boundaries. According to future developments expected by Haß et al. (2020), the income of arable farms will probably remain relatively stable until 2030 as will the demand for the crops considered in our model. This backs our approach. Wolf et al. (2015) likewise argue, that farm net income will probably remain stable in central EU regions affected by climate change until 2050. Possible changes to the acreages of individual crops are also expected to be in line with our specified restrictions (Haß et al., 2020). Nevertheless, unforeseeable events with major consequences for markets and demand, such as a global pandemic, for instance, can never be ruled out. These kind of events are not factored in our model. Hence, from the perspective of modelling and the individual farm, these future developments pose a challenge for the economic evaluation of biodiversity offset measures. This is because the costs of the measures must be calculated from today's perspective with regard to long-term expectations. We tried to depict the decision-making behaviour of farms in this context as accurately as possible, inter alia, by integrating the WTA as a form of risk premium.

All in all, the listed limitations and model uncertainties should be taken into account when interpreting the results. Nevertheless, the model results can be deemed to be highly informative for decision makers when they look at the impact of the presented offset scenarios.

5.2.2. Limitations and uncertainties of the crop model Expert-N

In this section we take a closer look at the uncertainties that arise from the Expert-N soil-plant model library.

The atmospheric boundary condition were spatially explicit time series of climate model output, interpolated onto a regular 5×5 km^2 grid. Importantly to note, is that climate models contain great uncertainties and weather data for individual years cannot be derived from such data. Consideration should be given to either their mean value or the trend over a long period of time. This also applies to the yields simulated on this basis. The high degree of uncertainty in future projections was taken into account in this study by using a climate model ensemble consisting of six ensemble members. Based on current climate developments, we classified the used climate scenario (RCP 8.5) as the most likely one. As lower boundary condition we used free drainage which is a robust choice since most soils in the Stuttgart Region have a large distance to the groundwater. Due to this and using an ensemble mean for the climate projections, we considered the uncertainties are small. The state and characteristics of the soil are included in the model as initial conditions. These values stemmed partly from a high-resolution soil map and partly from a model that linked the known soil texture to unknown soil properties. While the initial conditions do not affect the simulations beyond a couple of weeks, the soil properties may in fact lead to some systematic differences. These, however, could be considered negligible since we used the same properties in the model during calibration and therefore, the projections are congruent.

Crop management is a comparably high source of uncertainty when it comes to input data. These uncertainties stem from a lack of knowledge due to the lack of public data on crop management. Major efforts would be needed to overcome this uncertainty. We cannot accurately say how sensitive the yields are to management measures. This applies above all to site-specific amounts of nitrogen fertiliser – a matter that deserves further investigation, since at site level non-mean fertilisation regimes can affect the spatial distribution of yield change, which is of high relevance to this work.

We reduced the uncertainty arising from missing data on site-specific crop rotations by modelling the individual crops separately. Any negative effects of monocropping on soils and crop growth were circumvented in the model by adjusting the conversion rates for carbon and nitrogen prior to calibration in order to keep the nitrogen release rates in balance.

In the optimised model there were two main sources of uncertainty. The fitted parameters themselves were subject to uncertainty, in particular, as they were set manually in this study. However, we believe that a much higher level of uncertainty arises from the yield data on which the model was calibrated. They currently represent the best regional and publicly available yield reference data in Germany. But, averaged at district level, their sample size and the associated locations, i.e. soil and weather conditions, were not specified. Our calibration was, therefore, based on the assumption that these reference yields were representative for each district. Following the logic of Kirchner et al. (2021), for whom ignorance is also an uncertainty, we found that simulated average yields per district were less uncertain than the yields simulated for each individual field, since the goodness of fit of the former can be measured against reference data.

A comparison showed that the yields modelled with Expert-N are well within the range of the projections of other studies (see Section 3.1.2). Since this study focused on the localisation of compensation measures, the mean value of the yields was less relevant than their spatial distribution. This, in turn, depended more particularly on the spatial soil and weather input data, and was assigned a rather low level of uncertainty. Nevertheless, the effect of fertilisation on the spatial distribution should be further investigated.

5.2.3. *Integrated assessment and further assumptions of the model approach*

The prices per eco credit were estimated by comparing the net present values of the total gross margins in the scenarios. These were, therefore, average prices because the costs per eco credit locally could be significantly higher or lower, especially in the case of on-site offsetting. The estimated offset demand will not occur all at once, which means that an increase in prices over the years is to be expected. This is because the areas with the lowest opportunity costs would be used first. In this context, the use of the municipality as a spatial unit for on-site compensation must be taken into account. A higher spatial resolution could be used in the future, but urban land use planning is primarily up to the municipality as the decision-making planning unit. As an example, the city of Stuttgart strives to implement compensation within the city district (Koch, 2009). In the analysis, it was assumed that the need for compensation was completely covered on arable land. In practice and depending on the situation, however, implementation in areas outside of arable land may be preferable, for instance, in forests or along water bodies. In general, the average prices per eco credit we derived were consistent with the current market prices in Baden-Württemberg, which range from €0.50 to €1.10 depending on the location (Mössner, 2019).

Offset demand and assessment of the modelled biodiversity offset measures in eco credits was based on the respective habitat values in accordance with the *ÖKVO* in Baden-Württemberg. Diversity and quality of habitats are important attributes for characterising biodiversity. However, neither species nor genetic diversity was referred to in the study (Swingland, 2013). While plant species diversity tends to be associated with local management, vertebrate species are more responsive to landscape-level conditions (Gonthier et al., 2014). We used both the Shannon index and landscape connectivity to look at biodiversity on the landscape level. With regard to the connectivity of the landscape, we made the simplifying assumption that, in principle, all offset measures were equal in terms of their suitability as a connectivity element, i.e. habitat quality and patch size (Ramirez-Reyes et al., 2016). In addition, it must be considered that different species have different requirements with regard to the distance between patches (Tarabon et al., 2019). All in all, the interactions between biodiversity and habitats are complex, and this limited the meaningfulness of the results with regard to biodiversity improvement (Concepción et al., 2020).

When assessing landscape aesthetics, we used an index based on a survey carried out among the Swiss population, which has also been used in other comparable land use models, e.g. in Austria (Schönhart et al., 2016). Transferability, in principle, to the Stuttgart Region was assumed, especially since a large share of the respondents (ca. 58%) in the study also came from the peri-urban area (Schüpbach et al., 2009). We used the IACS dataset to quantify existing landscape elements and agricultural landscape use. Not all value enhancing elements were recorded in these data although they do currently provide the most consistent available representation for reliable quantification of diversity in the agricultural landscapes (Uthes et al., 2020). In order to also take into account general landscape quality, including elements outside the agricultural landscape, the land pixels were divided into three categories on an ordinal scale according to the overall rating levels of a state-wide landscape aesthetics assessment. A finer differentiation could have been undertaken, but the aim was to identify certain trends. Moreover, no statistical significance tests were carried out, and the results must be interpreted cautiously.

The WTA anticipated acceptance of the measures and, by extension, the likelihood of implementation from a DCE. Although the DCE is not generally representative for all farms in the Stuttgart Region, it did nevertheless cover a relatively high proportion of farms and was useful for our model. According to Sponagel et al. (2021), 65 out of 209 participants in the DCE came from five of the 6 districts in the Stuttgart Region. About 50% were part-time farmers, which is slightly below the average of about 61% in the Stuttgart Region (Stat. Landesamt BW, 2017). In addition, most farmers were aged between 40 and 50, which is representative for Baden-Württemberg (Stat. Landesamt BW, 2017). Farmsize varied between 21 and 220 ha with an average of about 67 ha. Small farms were thus underrepresented, which was also reported by similar DCEs, for instance Schulz et al. (2014). All the same the farms with more than 50 ha cultivated more than 50% of the agricultural area in the Stuttgart Region (Stat. Landesamt BW, 2017). Nevertheless, some farmers may not accept offset measures at all. Nonetheless, the issue of biodiversity in agricultural landscapes is gaining in importance, for instance in the EU Biodiversity Strategy. The agricultural sector is also beginning to recognise the societal demand for species and nature conservation (European Commission, 2020; Lange et al., 2015).

Furthermore, the study did not take into account land property rights as these data are not available in the spatial resolution required in Baden-Württemberg on data protection grounds. In the study, and especially with regard to the integrated WTA, it was assumed that farmers implement the offset measures on their own land. In principle, offset measures can also be implemented on third-party land by farmers, i.e. on land owned by the municipality (MLR, 2011). In this case, landlords could possibly demand a higher or lower WTA for the implementation of the measure.

5.3. *Role of biodiversity offsets for a sustainable agriculture*

According to Oppermann et al. (2020), there is a need for about 15–20% of high quality ecological land in the agricultural landscape for the sustainable protection and conservation of biodiversity. Offset measures can provide permanent high quality nature conservation areas which do not have to be publicly financed due to the polluter pays principle. They could account for up to about 10% of ecological areas on arable land, thus offering a relatively high potential for improving biodiversity in the agricultural landscape. At the same time, they may constitute an important business option, especially with regard to the diversification of farm activities (Meraner et al., 2015). Up to now, agri-environmental measures under the second pillar of the CAP alone were not able to achieve the desired effects in the context of biodiversity protection in Germany (Oppermann et al., 2020). Despite its major relevance in terms of biodiversity, the CAP does not contribute sufficiently to biodiversity conservation in the European context either (Pe’er et al., 2019). Mupepele et al. (2021) argue that a regional planning on the landscape level is very important for the improvement of biodiversity. In addition, they conclude that this has to be undertaken in cooperation with agriculture as farmland is often privately owned. Another determining factor is the proper motivation of farmers. Consequently, voluntary offsets measures – a business option for farmers – could also be a relevant instrument for biodiversity enhancement in a broader international context.

6. Conclusions

Using an interdisciplinary modelling approach with the inclusion of relevant stakeholders, we were able to demonstrate the economic and ecological implications of different compensation scenarios, with real data from an important prosperous region. To the best of our knowledge, this is the first time this has been done in Germany. This study thus contributes to the research field of spatial design and the implementation of biodiversity offsets (Gelcich et al., 2017; Gonçalves et al., 2015). The model results can thus illustrate the effects of different policy measures to decision-makers. Note should also be taken of the described model limitations and uncertainties. Our results are particularly important in the context of balancing individual goals, for instance, economic, ecological or local food supply objectives. This trade-off constitutes a major challenge when implementing biodiversity offsets.

The results showed that on-site compensation measures close to the intervention site can lead to additional costs. At the same time, they may be associated with ecological and social added values such as visual landscape quality. Furthermore, we concluded that a free market mechanism might lead to the lowest costs but it may also result in greater polarisation between urban and rural areas. This contrasted with other studies, which showed that urban populations, in particular, are highly appreciative of the services provided by agriculture in terms of the environment and landscape, which have a direct impact on quality of life (Zasada, 2011). Based on our results, we do not, therefore, recommend a spatially unrestricted market for biodiversity offsets. We likewise agree with Tallis et al. (2015) that assessments based on habitat values, for instance according to the *ÖKVO*, might ignore the contribution of measures to overall landscape functionality. In addition, the implementation of measures within a spatially restricted area, such as the applied search area map, might lead to comparatively high costs. Besides additional legal requirements, such instruments might be applied in a limited way in practice. Additional incentives, like a more in-depth evaluation of the measures, could be required to secure the spatial planning impact of a search area map, for example. Approaches of this kind have already been adopted in other Germans states such as Schleswig-Holstein and are set out in the Eco Account Regulation (Annex 1 ÖkokontoVO), for example. Although the results might not be representative for all German or European metropolitan areas, they can be highly informative for the planning of biodiversity offsets in similar urban areas. In the context of spatial planning, there are various legal means to encourage the implementation of biodiversity offsets. From a supra-local perspective, mention should be made more particularly of biotope network planning, in addition to the landscape master plans (§ 10 *BNatSchG*). Public planning authorities have to take biotope network concerns into account in all their planning activities, including compensation in Baden-Württemberg (§ 22 *NatSchG BW*). At the local level, the landscape plan should be mentioned in this context. It sets out the objectives and measures for nature conservation and landscape management at the municipal level (§ 11 *BNatSchG*). This also includes areas that are particularly suitable for the implementation of compensation measures (§ 9 *BNatSchG*). However, this is primarily about long-term and perspective planning. A current study in the Stuttgart Region by Jenssen (2020b) showed, however, that only about half of the municipalities address the issue of locating measures or planning eco-account measures in their landscape plan. According to the aforementioned study, scarcely any municipality was concerned about the future need for compensation. Against the backdrop of the study results and the potential added value of compensation close to the impact, the landscape plan could be brought more into focus as a medium of local spatial planning from a political perspective.

We further concluded that food production and supply as a whole should be considered when implementing offset measures on arable land. Approaches to protect high quality soils in the context of food security have already been adopted in countries such as Switzerland, where a certain contingent of what are known as “Fruchtfolgeflächen” (crop rotation areas) according to the Sectoral Plan on Crop Rotation Areas, must be earmarked for each canton (ARE, 2020). In this context, our modelling approach could serve as a helpful foundation as agricultural production is represented with high spatial resolution. Such approaches could also contribute to improved acceptance of these measures in agriculture, as farmers see securing the food supply as their most important societal responsibility, along with other goals such as nature conservation (Home et al., 2014).

Our model results could also be used for further investigations in terms of the ecological assessment of the outcomes of the scenarios. Therefore, a landscape functional connectivity model could be used that is based on several main species (Tarabon et al., 2021).

As our study mainly focused on the location of offset measures, there is a need for further research into the interactions between sites and types of offset measures depending on the habitat loss resulting from the intervention, i.e. in-kind or out-of-kind compensation approaches. In addition, the question arises as to the extent to which the IMR could be optimised through a more spatially differentiated assessment of measures in order to develop improved control instead of resorting to stricter legal requirements.

Declarations of Interest

None.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2022.106085.

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